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ORIGINAL PAPER

Effect of forest thinning on soil net nitrogen mineralization and nitrification in a *Cryptomeria japonica* plantation in Taiwan

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Abstract: We investigated the effect of forest thinning on soil nitrogen mineralization, nitrification and transformation in a *Cryptomeria japonica* plantation at high elevation to provide basic data for forest management. We chose four study plots for control, light, medium and heavy thinning treatment, and three sub-plots for buried bag studies at similar elevations in each treatment plot to measure the net N mineralization and nitrification rates *in situ*. The contents of soil inorganic N (ammonium and nitrate) were similar between treatments, but all varied with season, reaching maxima in September 2003 and 2004. The seasonal maximum net Nmin rates after four treatments were 0.182, 0.246, 0.303 and 0.560 $mg \cdot kg^{-1} \cdot d^{-1}$ in 2003, and 0.242, 0.258, 0.411 and 0.671 $mg \cdot kg^{-1} \cdot d^{-1}$in 2004, respectively. These estimates are approximate with the lower annual rates of N mineralization for this region. Forest thinning can enhance net N mineralization and microbial biomass carbon. The percentage of annual rates of Nmin for different levels of forest thinning compared with the control plot were 13.4%, 59.8% and 154.2% in 2003, and 0.1%, 58.8% and 157.7% in 2004 for light, medium, and heavy thinning, respectively. These differences were related to soil moisture, temperature, precipitation, and soil and vegetation types. Well-planned multi-site comparisons, both located within Taiwan and the East-Asia region, could greatly improve our knowledge of regional patterns in nitrogen cycling.

Keywords: *Cryptomeria japonica* plantation, forest thinning, nitrification, seasonal variation, soil nitrogen mineralization

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Introduction

Nitrogen (N) is a major limiting factor for forest growth and productivity of the terrestrial ecosystem (Keeney 1980; Binkley and Hart 1989; Paul and Clark 1989; Vitousek and Howarth 1991). Plants absorb N mainly in inorganic forms that can be converted from soil organic N through the process of mineralization. Natural or anthropogenic disturbances can affect forest soil ecosystems and soil N transformation processes both in direct and indirect ways. Forest pre-commercial thinning is a common practice of removing some trees in immature stands to enhance growth of the remaining trees, thus improve the total yield or value of usable wood. Thinning entails severe disturbance that can be expected to result in many changes to a forest. Many studies have characterized the response of soil N transformation to forest thinning (Powers 1990; Gessel et al. 1990; Dyck et al. 1994; Thibodeau et al. 2000). But the impacts of forest thinning intensity have not been studied.

Because of high mineralization and nitrification, NH_4^+ and NO_3^- concentrations show the greatest proportional increases after thinning (Baeumler and Zech 1998), while net N mineralization declined in thinned balsam fir (*Abies balsamea* (L.) Mill.) plots (Thibodeau et al. 2000). Both studies showed greatly increased NH_4^+ in thinned plots. Post-thinning changes in soil temperature and moisture are important in interpreting the impacts of this disturbance on soil nutrient transformations and sustainability of fertility (Entry et al. 1986; Thibodeau et al. 2000).

In Taiwan, forests cover almost 2/3 of the total land area and 1/3 of the forested area is comprised of single-species plantations that were planted several decades ago. In accord with current trends in economic development, the goals of forest management for pure commercial production are being changed to serve ecological and environmental functions. In this changing environment, there is a potential to modify the current policy favoring plantation mono culture to increase forest biodiversity through thinning and re-forestation. Nevertheless, there are few studies

on the impact of thinning on nutrient transformation of the mono culture forest plantation soil, especially in the mountain areas of Taiwan. Thus, we aimed to investigate the effects of forest thinning intensity on soil N mineralization and nitrification in a *Cryptomeria japonica* plantation at high elevation to provide basic data for forest management and to enhance our understanding of the influence of forest thinning on soil nutrient transformation.

Materials and methods

Site and thinning

This study was conducted in a 30-year-old *Cryptomeria japonica* plantation located at Guanwu resort region, Chu-Tung, Hsin-Chu County, northern Taiwan (Fig. 1). The study site is a mountainous area with elevations ranging from 1,900 to 2,250 m. Mean annual precipitation is 2,500 mm, occurring mainly between May and September, characteristically as thunderstorms associated with typhoons. Mean annual temperature in 2003−2004 was 12.5°C with a range of 6.5−18°C. Soil parent materials are sandstones and clay sediments interbedded with tertiary shale and slate (Ho 1988).

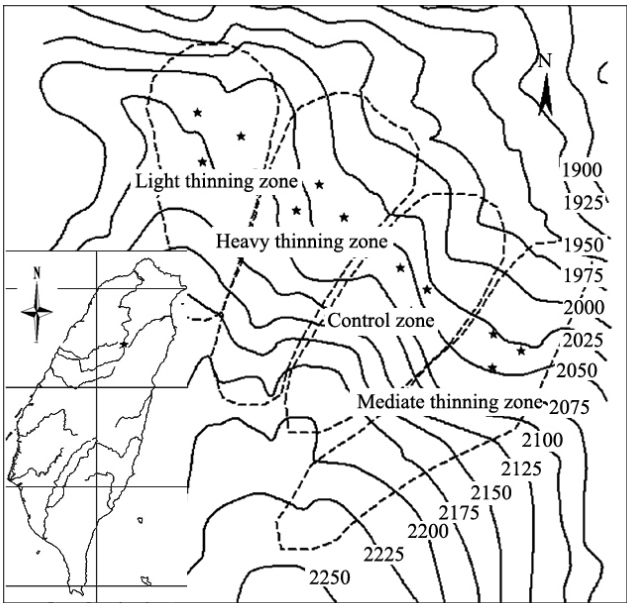

Fig. 1: Topographic map of the sampling sites (stars represent sampling points)

Experimental design

The total area of the plantation was 29 ha and four plots were set up in early 2002 to represent four intensities of forest thinning, control (0%), light (40%), medium (53%) and heavy (67%) thinning. The project's purpose was to investigate the effect of forest thinning intensity on forest production and biodiversity to provide information for the government in policy decision making. As one part, we focused on the change in soil N mineralization and nitrification after the thinning. The thinned stand density was 1500, 900, 700 and 500 trees per ha for the control, light, medium and heavy thinning by even-gap thinning, respectively. The thinned trees were left on the forest floor in packs near the plots not inside the plots. After thinning, we located and marked five plots in each thinning treatment at each site. Study zones were separated by 50 m and sub-plot size was 2 m × 2 m in each thinning treatment. Plots were randomly located within each zone. Five soil samples in each plot were collected from the O/A horizon (10−20 cm) by completely randomized designed (CRD) for soil physical and chemical analyses. The soils were previously classified as sandy loam or silty loam, mixed, mesic, and Typic Dystrudepts (Soil Survey Staff 2006).

Soil temperature and moisture

After the thinned treatment setup, soil temperature and moisture were monitored continuously with Watch Dog Model 450 Datalogger (Spectrum USA), which comprises an external soil temperature sensor 3667 and a Watermark soil moisture sensor 6450D, in the four plots. The sensors were buried in mineral soils at 10-cm depth to measure soil temperature and moisture. The air temperature was measured at the height of 70 cm above the soil surface.

Determination of soil net N mineralization and nitrification rate

Soil net N mineralization and nitrification rates were estimated *in situ* using a buried polyethylene bag technique (Eno 1960; Hart and Firestone 1989). Briefly, a pair of soil samples was collected from 10−20 cm below the soil surface and put into polyethylene bags. One sample bag was buried back in the original sampling hole and covered with litter. The other sample was taken back to the laboratory for analysis. Soil net N mineralization and nitrification rates were calculated from the difference in NH_4^+-N + NO_3^--N and NO_3^--N before and after incubation. The polyethylene bags (thickness of about 30 µm) allowed O_2 and CO_2 diffusion, so aerobic conditions were maintained in the isolated soil, as were temperature patterns and soil moisture content at the time of sampling. Five replicate samples were collected at each subplot and incubated for three months, i.e., every three months from December 2002 to December 2004.

Soil analysis

The pH of soil samples was measured in distilled water (soil to solution = 1:5 w/w). Total C and N contents of the soils were determined by a CHN analyzer (Carlo Erba analyzer, Milan, Italy). Cation-exchange capacity (CEC) of the soils was determined using the ammonium acetate (NH_4OAc) exchange method (Rhoades 1983). Exchangeable cations in supernatants were extracted by 1 *M* NH_4OAc (pH=7.0) solutions. Na, K, Ca and Mg contents were determined by conductivity coupled plasma atomic emission spectroscopy (ICP-AES) (Perkin Elmer Optima 2000DV). The freeze-dried soils (particle size <2 mm) were

suspended in distilled water and dispersed by ultrasonication. The dispersed soils were separated into clay, silt and sand fractions by sedimentation and centrifugation for soil texture analysis (Jackson 1979). We estimated soil bulk density using the core method, where the oven dry weight of soil was divided by the volume of the core (Blake and Hartge 1986).

Soil microbial biomass carbon was determined by the fumigation-extraction method (Vance et al. 1987). Soil sample (25 g) at 40% of water-holding capacity was fumigated with ethanol-free chloroform for 24 h at 25°C. After fumigation and chloroform removal, it was extracted with 200 mL 0.5 M K_2SO_4 solution for 30 min. The non-fumigated control soils were extracted under the same conditions at the same time. Organic carbon and nitrogen in the extract were measured by wet digestion with dichromate and titration with $FeSO_4$ solution and Kjeldahl digestion, respectively. Subsoil samples of each soil were also weighed and oven-dried at 105 °C to determine moisture content. Microbial biomass carbon was calculated as the difference in carbon content between non-fumigated and fumigated soil extracts (Yang et al. 2003).

Soil samples were sieved and passed through a 2-mm sieve. A sub-sample was used to measure moisture content at 105°C overnight until constant weight was achieved. Fresh soil samples (10 g) were extracted with 100 mL 2 *M* KCl solution on a reciprocal shaker for 60 min. Soil extracts were filtered through Whatman No. 42 filter paper. Ammonium concentrations for the filtrates were determined using a manual indophenol colorimetric method (Dorich and Nelson 1983). Nitrate concentrations were determined using the manual Cd reduction method (APHA 1998). Net N nitrification rate was calculated as the difference in NO_3^--N concentrations between the incubated sample and the initial samples. Annual rates of net N mineralization and nitrification were estimated by summing all monthly values (Owen et al. 2003). Net N mineralization and nitrification rates were converted to mass per area per unit time using the bulk density estimates.

Statistical analysis

Differences between the four thinning levels were analyzed using analysis of variance (ANOVA) for the test of determination coefficient (R2), level of significance (p-value), standard error (SE), and the least significant difference (LSD). The LSD values were calculated using SE and *t* values at appropriate degrees of freedom at 95% confidence levels.

Results and discussion

Soil temperature and moisture

Soil temperature varied with thinning intensity in summer (p =0.001), but not in winter. Mean soil temperature after heavy thinning increased by 0.7°C (p =0.02) in summer 2003 and 0.5°C in summer 2004. Thinning did not affect soil moisture (Fig. 2), but medium intensity thinning showing the highest variation in soil moisture. At the end of the observation period, soil moisture differed with treatment because rainfall during the final three months of study dropped greatly from 1000 mm to 10 mm. The control plot had the lowest soil moisture and this might have resulted from the growth of surface vegetation. Generally, soil temperature and moisture are influenced greatly by land cover (Venkatesh et al. 2011).

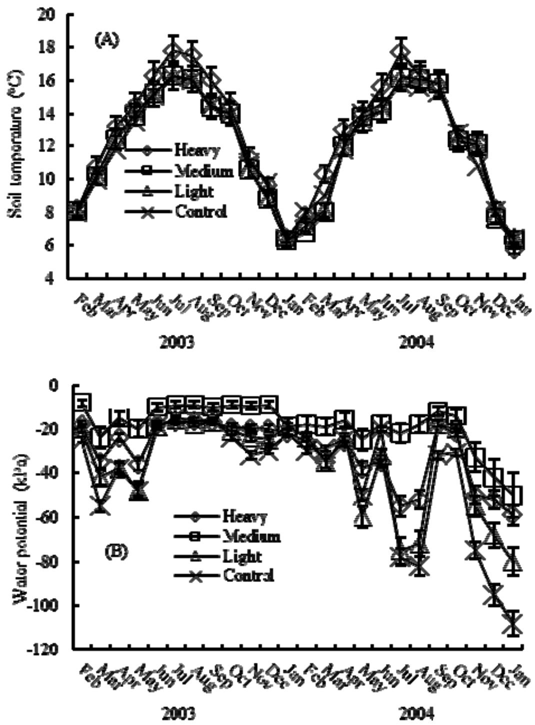

Fig. 2: Mean soil temperature (A) and water potential (B) by level of thinning intensity

Temperature and moisture are the most important environmental factors on soil N transformation (Frederick 1956; Standford and Epstein 1974; Powers 1990; Nicolardot et al. 1994; Knoepp and Swank 2002). The effect of soil moisture on N mineralization can be described by a linear model, while that of temperature follows an exponential model (Wang et al. 2004). However, Knoepp and Swank (2002) indicated that soil moisture acts as a correction term for the exponential response of N mineralization to temperature. Nicolardot et al. (1994) reported that temperature influenced the movement of labeled C and N through microbial biomass and maximum mineralization rates, which occurred between 20°C–28°C. Standford and Epstein (1974) examined the relationships between soil moisture and Nmin for nine different soil types. Maximum mineralization rates occur at soil matrix potentials of 0.3 to 0.1 MPa (about 10%–35% moisture by weight), but temperature shows only little effect in limiting increasing soil moisture content (Knoepp and Swank 2002).

Water content in the thinned plots was higher than in the control, but the order is not consistent with that of temperature for different thinning. This is mainly due to the spatial variations of the plots, where the medium-thinning is performed on a

north-facing slope that received more precipitation than the other plots. At the same time, water potentials of all treatment plots are lower than 0.1 MPa, suggesting that moisture is not a limiting factor on soil N mineralization. Thus, the change in temperature after thinning, rather than moisture, is the dominant factor affecting soil N mineralization. As conducted in the same plots, the mean values of microbial biomass C of control were in 735±32–425±22 $\mu g \cdot g^{-1}$ dry soil (Yang et al., 2003). The microbial biomass C increased with the increasing degree of forest thinning, suggesting the forest thinning affected soil N mineralization through temperature.

Soil basic physical and chemical properties

The post-thinning physical and chemical properties of soil are listed in Table 1. Soil pH of 5.12 was highest in the control plot, and soil pH of 3.67 was lowest in the light-thinning plot. Total C and N were highest in the light-thinning plot. Cation-exchange capacity (CEC) and clay contents were similar in all thinning treatments. Base saturation (BS, %) was higher in the control and medium-thinning plots but lower in the light- and heavy-thinning plots. The soil texture ranged from sandy loam to silt loam. The contents of total N and C, and C/N ratios showed a declining trend of light thinning > heavy thinning > medium thinning > control.

Soil pH can affect soil microbial activity and relate to N transformation, so the lower pH greatly decreases N nitrification (Frederick 1956). However, there is no direct relationship between soil pH and N mineralization rate (Hassink 1992; Piccolo et al. 1994, Laverman et al. 2000). Soil C/N ratio is one of the important factors controlling the N mineralization process (Matson and Vitousek 1981; Bengtsson et al. 2003). It is assumed that microbes may be N-limited in soil with C/N ratio above 20 and C-limited in soil with C/N ratio below 20 (Tate 1995). The soil C/N ratios of the study plots ranged from 14.6 to 18.2 and showed no significant differences (Table 1). Cation-exchange capacity (CEC) and base saturation (BS) are less relevant to N mineralization (Bonilla and Roda 1992, Bengtsson et al.2003). Soil texture and structure may affect C and N mineralization rates, thus accounting for most of the variations in soil C and N content (Hassink 1992; Six et al. 1999; Giardina et al. 2001). Similar clay content and soil texture of the four plots caused no significant difference in N mineralization among them (Table 1). Owing to the inconsistencies of the basic soil physicochemical properties of the treatment plots, the soil spatial variations could have a great effect on the results of thinning.

Table 1: Selected soil physical and chemical properties of soil tested (initial)

Treatment	pH	Total C (%)	Total N (%)	C/N	CEC($cmol \cdot kg^{-1}$)	BS (%)	Sand (%)	Silt (%)	Clay (%)	Texture
Control	5.12^{ba}	12.0^{b}	0.82^{ab}	14.6	25.3^{a}	15.2^{a}	30.7	51.8	17.5^{a}	Sandy loam
Light	3.67^{b}	18.9^{a}	1.04^{a}	18.2	21.8^{a}	7.5^{b}	20.5	62.1	17.4^{a}	Silt loam
Medium	4.98^{a}	13.0^{ab}	0.75^{b}	17.3	24.1^{a}	18.1^{a}	37.1	47.3	15.6^{a}	Sandy loam
Heavy	3.78^{b}	15.0^{a}	0.83^{ab}	18.1	28.1^{a}	4.6^{b}	14.4	65.4	20.2^{a}	Silt loam

BS: base saturation; CEC: capacity of exchangeable cation; Different letter represents a significant difference at 95% level (p=0.05, n=5)

Soil inorganic N varied with seasons

There were seasonal variations in individual extractable inorganic N (NO_3^--N, NH_4^+-N and NO_3^--N+NH_4^+-N) by thinning treatment, showing two cycles of higher NO_3^--N, NH_4^+-N and NO_3^-N+NH_4^+-N contents in June-September of 2003 and 2004 (Fig. 3). Lower inorganic N contents were seen in December to March in both 2003 and 2004. The nitrate contents were 3.73–14.2, 2.45–10.25, 4.21–15.9 and2.89–19.2 $mg \cdot kg^{-1}$ for control, light-, medium- and heavy-thinning treatments (Fig. 3A), while the corresponding ammonium concentrations were 2.14–9.31, 1.56–8.66, 2.01–15.4 and 4.21–7.79 $mg \cdot kg^{-1}$, respectively (Fig. 3B). Inorganic N of all thinning treatments was highest in September at 17.1, 26.1, 23.5 and 27.8 $mg \cdot kg^{-1}$ in 2003, and 18.60, 18.85, 28.30 and 25.40 $mg \cdot kg^{-1}$ in 2004, respectively (Fig. 3C). Compared with the control, the LSDs of all thinnings were significantly higher ($LSD_{0.01}$ = 3.21) in 2003. There was no consistent relationship between inorganic N content and level of thinning intensity.

Soil net N mineralization and nitrification

Of all treatments, the highest soil net N mineralization rate occurred in June to September in both 2003 and 2004.The highest net N mineralization rates were 0.182, 0.246, 0.303 and 0.560 $mg \cdot kg^{-1} \cdot d^{-1}$ in 2003, and 0.242, 0.258, 0.411 and 0.671 $mg \cdot kg^{-1} \cdot d^{-1}$ in 2004, for control, light-, medium- and heavy-thinning, respectively (Fig. 4A). Similarly, the highest net N nitrification rates were 0.177, 0.198, 0.284 and 0.259 $mg \cdot kg^{-1} \cdot d^{-1}$ in 2003, and 0.231, 0.242, 0.289 and 0.334 $mg \cdot kg^{-1} \cdot d^{-1}$ in 2004 for control, light-, medium- and heavy-thinning, respectively (Fig. 4B).

Thinning reduces stand density and increases radiation and temperature as well as water content of the soil (Sucoff and Hong, 1974; Thibodeau et al., 2000). Our results obtained shortly after thinning are in agreement with such a trend (Fig. 2). The mean soil temperature of all plots ranged from 0–20°C, and the soil N mineralization showed sensitivity to temperature change. Thus, the increase in temperature after thinning might have been responsible for the higher N mineralization rates of the thinned plots, showing two cycles of higher NO_3^--N, NH_4^+-N and NO_3^--N+NH_4^+-N concentrations between June and September in 2003 and 2004. The seasonal variations in N mineralization rates correspond to the seasonal pattern of soil temperature and moisture (Nadelhoffer et al. 1984; Adams and Attiwill 1986; Strader et al. 1989; Bonilla and Roda 1992; Knoepp and Swank 1998).

In our study, the relationship between N mineralization and mean soil temperature was described as: N mineralization rate = 0.0269 T-0.1355, $R^2 = 0.5121^{**}$ (n =48). However, the effect of forest thinning on N mineralization varied with seasons (Fig. 4), suggesting that the mineralization process is controlled by the environmental factors such as rainfall and temperature.

In general, low contents of nitrates occur in forest soils. Many researchers suggested that the patterns of nitrate production in forest soils are regulated by soil pH, NH_4-N availability and the presence of compounds in the soil that inhibit nitrification (Robertson 1982; Olson and Reiners 1983; Lensi et al. 1986; Donaldson and Henderson 1990; Laverman et al. 2000). We documented a high soil nitrification rate that accounted for almost 86% of the N mineralization rate. The high nitrification potential at the study site was mainly due to the soil coarse texture in a subtropical region with high temperature and rainfall (Table 1).

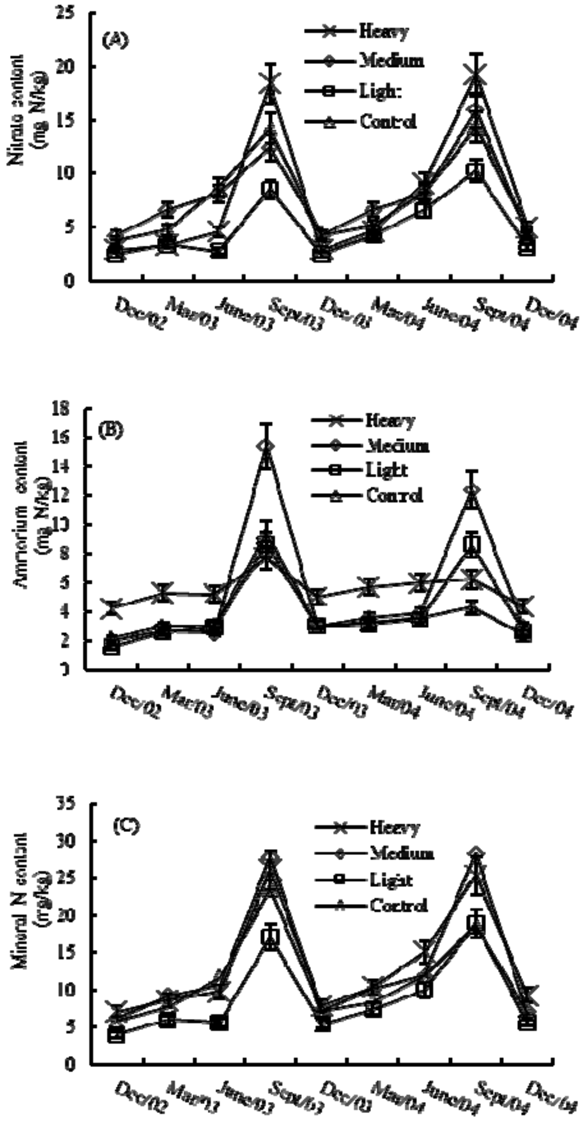

Fig. 3: Inorganic N contents in forest soils from buried bags: (A) nitrate-N; (B) ammonium-N, and (C) total inorganic N, varied with seasons

We documented an annual cycle of N contents and transformations (Figs. 3 and 4). The cycle was consistent with soil temperatures (Fig. 2) but not with soil moisture, suggesting that temperature was the main control factor affecting soil N transformation at our high elevation sites. This result also indicates that the effect of forest thinning on soil N transformation occurs through entailing changes in soil temperature.

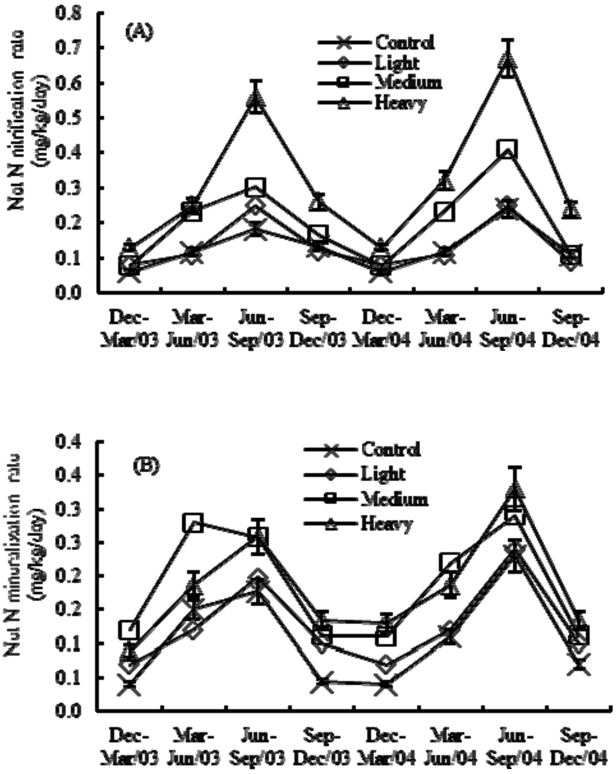

Fig. 4: Net N mineralization (A) and nitrification (B) rates by level of thinning intensity from December 2002 to December 2004

The amounts of soil net N mineralized increased with the increasing thinning intensity (Fig. 5). The highest rate reached 107.9 $mg \cdot kg^{-1} \cdot a^{-1}$ and the ratio of mineralized N to total N was about 1.30% in 2003, and 122.4 $mg \cdot kg^{-1} \cdot a^{-1}$ and 1.47% in 2004 on heavily thinned plots. Increase in soil temperature stimulates microbial population and improves the net N mineralization after thinning (Thibodeau et al. 2000). The net N mineralization increases after thinning, indicating that only a portion of the mineralized N is incorporated by microbes. Moreover, thinning reduces the inorganic N uptake by plants (Matson and Boone 1984; Baeumler and Zech 1998). Thus, the larger amount of mineralized N in the thinning treatments suggests a great loss of inorganic N from the plots after heavy thinning. However, there was no direct evidence to indicate post-thinning loss of N at other intensities of thinning. During the short experimental run, thinning showed significant effects on N mineralization and nitrification in our study site, but an integration of N balance estimation merits further study.

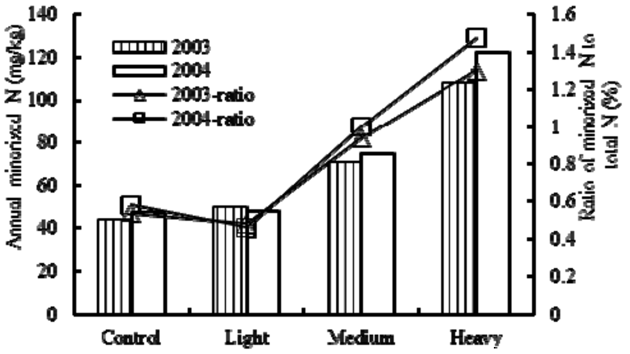

Fig. 5: Accumulation of mineralized N during two years of study after thinning

Estimates of annual N mineralization rates

Our estimates of annual rates of N mineralization are compared with other published estimates of annual N mineralization from forested ecosystems in Asia and North America. The annual net Nmin of the control plot was 10.6 and 11.4 kg·ha^{-1}·a^{-1} in 2003 and 2004, respectively. These estimates are comparable with the lower annual rates of N mineralization for this region (Table 2). In general, forest thinning treatments can enhance net N mineralization. The increase in percentage of annual rates of N mineralization for different forest thinning treatments compared with the control plot were 13.4%, 59.8% and 154.2% in 2003, and 0.1%, 58.8% and 157.7% in 2004 for light, medium and heavy thinnings, respectively (Table 3). These differences might be related to many factors, including differences in soil moisture and temperature, precipitation, soil types, and vegetation types. We believe that these differences merit further study and hope that our results will encourage future multiple-site comparisons of watershed N cycling processes within the East-Asia Pacific region. Well-planned multi-site comparison, both located within Taiwan and the East-Asia region, could greatly improve our understanding of regional patterns in nitrogen cycling.

Conclusions

Forest thinning significantly increases soil temperature in plantations at high elevation rather than moisture. Change in temperature affects N mineralization. Therefore, N mineralization increases with thinning because of temporary increases in soil temperatures and moisture. Soil net N mineralization and nitrification rates increase greatly after thinning, but soil inorganic N showed no significant difference among the treatments, suggesting a great loss of N after forest thinning. Forest thinning can enhance net N mineralization with increasing soil microbial biomass. However, the difference in both temperature and N transformation attributed to thinning diminishes with time. Our findings are useful for interpreting ecosystem's function in response to thinning management.

Table 2: Comparison of annual rates of N mineralization from related studies in Asia, North America and Sweden

Dominant species	Location	Nmin (kg·ha^{-1}·a^{-1})	Reference
Cryptomeria japonica	Japan	67	Wu et al. 1998
Chamecyparis obtuse		77	
Cryptomeria japonica 15 year	Japan	58	Murakami et al. 1990
Chamaecyparis obtuse 15 year		34	
Chamaecyparis obtuse 35 year		22	
Tsuga chinesis var. *formonsana*	Taiwan	34	Owen et al. 2003
Miscanthus transmorrisonesnsis Hayata		11	
Pinus kesiya 7 year	India	85	Maithani et al. 1998
Quercus dealbata 13 year		106	
Q. dealbata/Rhododendron arboream 16 year		115	
Acacia catechu/Emblica officinalis hillbase	India	210	Raghubanshi 1992
A. catechu/lannea coromandelica		170	
Boswellia serrata/A. catechu		200	
Sugar Maple	Canada	144	Ste-Marire and Houle 2006
Balsam Fir		76	
Black Spruce		1	
Mature forest, Ecuadorian Andes	USA	118	Rhoades and Coleman 1999
Spruce–Fraser fir Appalachians	USA	103	Strader et al. 1989
Hemlock Upper Michigan	USA	89	Mladenoff (1987)
Spruce–fir Adirondacks	USA	40	Friedland et al. (1991)
Douglas fir Oregon	USA	6	Myrold et al. (1989)
Lupinus nootkatensis Donn	Sweden	178	Myrold and Huss-Danell 2003
Alnus incana (L.) Moench		32	
Cryptomeria japonica (control plot)	Taiwan	10.6 (2003), 11.4 (2004)	This study

Table 3: Annual net N mineralization (kg·ha^{-1}·a^{-1}) and percentage to the control

Plot	2003 (kg·ha^{-1}·a^{-1})	Percentage (%)	2004 (kg·ha^{-1}·a^{-1})	Percentage (%)
Control	10.6 (44.0)*	-	11.4 (47.5)	-
Light	12.0 (49.9)	13.4	11.5 (47.7)	0.1
Medium	16.9 (70.3)	59.8	18.0 (74.8)	58.8
Heavy	26.0 (107.9)	145.2	29.4 (122.4)	157.7

* Unit of the net Nmin in parenthesis is mg·kg^{-1}·a^{-1}.

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